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Roles of saltcedar (*Tamarix* spp.) and capillary rise in salinizing a non-flooding terrace on a flow-regulated desert river☆

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ABSTRACT

Tamarix spp. (saltcedar) secretes salts and has been considered to be a major factor contributing to the salinization of river terraces in western US riparian zones. However, salinization can also occur from the capillary rise of salts from the aquifer into the vadose zone. We investigated the roles of saltcedar and physical factors in salinizing the soil profile of a non-flooding terrace at sites on the Cibola National Wildlife Refuge on the Lower Colorado River, USA. We placed salt traps under and between saltcedar shrubs and estimated the annual deposition rate of salts from saltcedar. These were then compared to the quantities and distribution on of salts in the soil profile. Dense stands of saltcedar deposited 0.159 kg m^{-2} yr^{-1} of salts to the soil surface. If this rate was constant since seasonal flooding ceased in 1938 and all of the salts were retained in the soil profile, they could account for 11.4 kg m^{-2} of salt, about 30% of total salts in the profile today. Eliminating saltcedar would not necessarily reduce salts, because vegetation reduces the upward migration of salts in bulk flow from the aquifer. The densest saltcedar stand had the lowest salt levels in the vadose zone in this study.

1. Introduction

In their natural state, many arid zone rivers have a pulse-flood flow regime, which produces seasonal overbank flooding. Floods refresh the alluvial aquifer, leach salts from the soil and allow mesic vegetation to establish on the terraces (Poff et al., 1997). Many arid zone rivers are now flow-regulated to prevent overbank flooding. No longer do floods or high water tables flush out salts periodically, and salts tend to accumulate in the aquifer and soil profile over time on these rivers (Poff et al., 1997; Jolly et al., 2008).

In the southwestern U.S., many flow-regulated (non-flooding) rivers have come to be dominated by saltcedar (*Tamarix ramosissima* and related species and hybrids) (Gaskin and Schaal, 2002), an imported halophyte shrub from Eurasia (Ungar, 1991; Glenn and Nagler, 2005; Pataki et al., 2005; Nagler et al., 2010). Saltcedar typically extracts water from aquifers as deep as 8–12 m below the soil surface (Bruelheide et al., 2010). However, it can also utilize water from the unsaturated zone if the connection with the aquifer is broken (Nippert et al., 2010). Saltcedar actively excretes salts from its leaves via salt glands (Storey and Thomson, 1994), and it has been commonly assumed that saltcedar is a major contributor to the salinization of riparian soils through deposition of exudates and salt-laden leaf litter, resulting in the competitive exclusion of mesic native trees such as cottonwood (*Populus* spp.) and willow (*Salix* spp.) from saltcedar-dominated river terraces (Brotherson and Field, 1987; Di Tomaso, 1998; Zavaleta, 2000). As a corollary, it has sometimes been assumed that removing saltcedar can allow the return of mesic native vegetation to floodplains (e.g., DeLoach et al., 2000).

Only a few previous studies have attempted to quantify the role of saltcedar in salt deposition, however, and these demonstrate complexities in the relationships among saltcedar, salty soil and native plant regeneration (Morris et al., 2009). Ladenburger et al. (2006) reported that soil salinity levels were higher under saltcedar shrubs compared to between shrubs, but that salt levels were not high enough to disrupt the germination of native shrubs and trees at riparian sites in Wyoming, USA. Lesica and DeLuca (2004) also reported elevated salt levels under saltcedar shrubs, but germination of a native grass was actually higher on these soils than on control soils, and they concluded that saltcedar is not allelopathic. Ohrtman (2009)

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reported elevated salt levels under saltcedar plants in both flooding and non-flooding sites on the Middle Rio Grande, New Mexico, USA, but salt levels were paradoxically lowest under the oldest saltcedar plants, and were not so high that restoration with native vegetation would be inhibited by salinity. Yin et al. (in press), working in the native range of saltcedar in Asia, reported that salt levels were higher in saltcedar mounds than between mounds, but that fertility factors such as potassium, organic matter and phosphorous were also higher, and that saltcedar mounds were overall a net positive factor in rehabilitating soils for restoration.

The above studies looked only at the role of saltcedar leaf exudates and litter in salinizing riparian areas. However, other processes can also contribute to salinization. Hydraulic lift of saline groundwater by salt-tolerant vegetation can deposit salts in the vadose zone, for example (Armas et al., 2009). Another source of salts in riparian soils is capillary rise of water and salts from the aquifer into the vadose zone (Gillham, 1984; Silliman et al., 2002). The capillary fringe can extend to 1–3 m above the water table, with fine textured soils supporting greater rise than sands (Gillham, 1984; Gerla, 1992; Kuo, 1999). Salts can accumulate to high levels in this zone due to the evaporation of water from the top of the capillary fringe or soil surface and deposition of salts in the vadose zone (Doering et al., 1964; Gerla, 1992; Costelloe et al., 2009; Grunberger et al., 2008). In fact, this is one mechanism by which salt flats are formed (Kinsman, 1969). Evapotranspiration (ET) by deeply rooted vegetation can counter this effect, by limiting the rise of water and salts to the soil surface through evapotranspiration (ET)(e.g., Nosetto et al., 2007).

The present study examined the distribution of salts and soil moisture as a function of soil depth, texture and distance from the river on two saltcedar-dominated river terraces at Cibola National Wildlife Refuge (CNWR), California, on the Lower Colorado River (Fig. 1). The terraces at CNWR were formerly flooded via a series of overflow arms and backwaters of the river, but overbank flooding was markedly curtailed after 1938, when Hoover Dam was completed (Olmsted and McDonald, 1967). The possibility of floods was further curtailed after 1964 when the main river flow at CNWR was diverted from the natural river channel into an engineered channel surrounded by flood control levees (Fig. 1) (United States Bureau of Reclamation, 1996; 2008). The new channel supports flows of ca. 200–400 $m^3\ s^{-1}$, whereas the old channel now carries only 8–15 $m^3\ s^{-1}$ to support wildlife in the refuge (U.S. Bureau of Reclamation, 2008). Since 1938 the vegetation on the terraces has converted from a mix of mesic and salt-tolerant plants to saltcedar-dominated stands growing with native salt-tolerant plants such as quailbush (*Atriplex lentiformis*), arrowweed (*Pluchea sericea*) and stunted mesquites (*Prosopis* spp.) (Nagler et al., 2009).

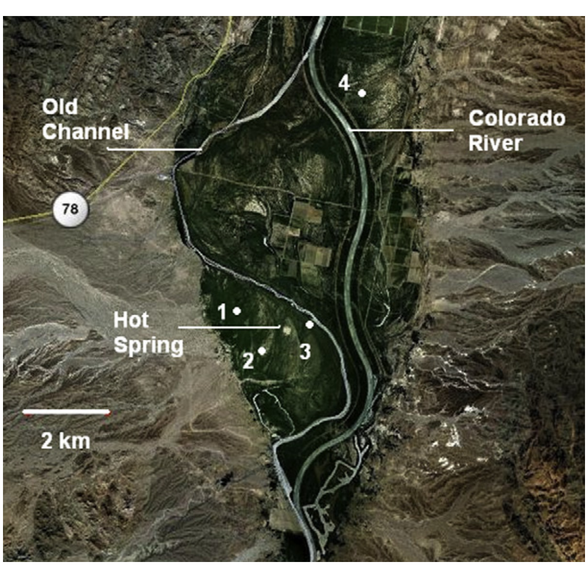

Fig. 1. Locator map of sites for soil salinity measurements: 1) Slithern; 2) Diablo; 3) Swamp; 4) Burro. Also shown is an area where geothermal water approaches the surface (Hot Spring); the old channel of the river; and the new channel of the Colorado River carrying most of the flow since 1964.

We used this site to study the effects of saltcedar and capillary rise on the salt balance of a non-flooding river terrace. We placed salt traps under saltcedar bushes to measure the rate of salt deposition from saltcedar leaf exudates and litter-fall, and took soil cores and aquifer samples to quantify the amount of salts present in the aquifer and vadose zone as a function of soil depth. Due to scarcity of floods and very low precipitation, our hypothesis was that most of the salts originating from saltcedar, capillary rise and other processes since 1938 would still be present in the profile, allowing us to elucidate the biological and physical processes responsible for salt deposition, and to create an approximate mass balance of sources of salt deposition on a non-flooding river terrace.

2. Methods

2.1. Study sites

CNWR is in an extreme arid environment in the Sonoran Desert. Mean annual precipitation is 100 mm yr^{-1}, and temperatures range from lows of 4 °C in January to highs of 45 °C in June and July. Weather data from 1938 to 2010 were obtained from the NOAA Cooperative Station at the Blythe Airport for the years 1935–2006 (Station 040924).

(http://www.wrcc.dri.edu/cgi-bin/cliGCStP.pl?ca0927 (040924) http://weather-warehouse.com/WeatherHistory/PastWeatherData_BlytheRiversideCntyArpt_Blythe_CA_August.html). Data after 2006 were from the Parker, Arizona AZMET station (AZMET, 2011). Potential evapotranspiration were calculated from annual mean temperature and latitude using the Blaney–Criddle formula (Brouwer and Heibloem, 1986).

The primary sampling sites (Fig. 1) are three locations where saltcedar ET was measured by sap flux sensors and Bowen ratio moisture flux towers which were used to measure ET in previous studies (Nagler et al., 2008; 2009; Chatterjee, 2010; Zhu et al., 2011; Taghvaeian, 2011). The sites were chosen to represent a gradient of saltcedar stand density and distance from the active river channel. They were given fanciful names based on summer working conditions. Slitherin was located in a very dense saltcedar stand approximately 750 m from the river; Swamp was in a medium dense stand 200 m from the river; and Diablo was in a less dense stand 1500 m from the river. Leaf area index (LAI) values were 4.6 at Slitherin, and 3.4–3.5 at Swamp and Diablo (Nagler et al., 2008; 2009). At each site five observation wells were drilled from the soil surface to the aquifer and fitted with a PVC casing to measure depth and salinity of the aquifer at monthly intervals and soil moisture in the vadose zone using a neutron hydroprobe (methods described in detail in Nagler et al., 2008; 2009). One well was located near the moisture flux tower and the other four were located at the corners of a 100 m × 100 m square around the central well. Soil moisture data were collected monthly, June to August, 2006, as reported in Nagler et al. (2008) and they are repeated here to put the salinity data in context. Additional soil moisture measurements were conducted at Swamp on June 8 and 9 to test for diurnal variations in vadose zone moisture content characteristic of hydraulic lift (Caldwell et al., 1998). Moisture reading were taken at each of the 5 observation wells at Swamp at 9 am and 3 pm on June 8 and at